

Two new AM Canum Venaticorum binaries from the Sloan Digital Sky Survey III

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ABSTRACT

The AM Canum Venaticorum (AM CVn) binaries are a rare group of ultrashort period, mass-transferring white dwarf binaries, some of which may be Type Ia supernova progenitors. More than a third of the total known population of AM CVn binaries have been discovered via the Sloan Digital Sky Survey (SDSS). Here, we discuss our search for new AM CVns in the SDSS spectroscopic data base, and present two new AM CVns discovered in SDSS-III spectroscopy, SDSS J113732.32+405458.3 and SDSS J150551.58+065948.7. The AM CVn binaries exhibit a connection between their spectral appearance and their orbital period, the spectra of these two new AM CVns suggest that they may be long-period systems. Using the radial velocity variations of the emission lines, we measure a possible orbital period of 59.6 ± 2.7 min for SDSS J113732.32+405458.3. Since our search of SDSS spectroscopy has revealed only these two new systems, it is unlikely that a large population of AM CVn binaries have been missed, and their discovery should have little effect on previous calculations of the AM CVn space density.

Key words: accretion, accretion discs – binaries: close – stars: individual: SDSS J113732.32+405458.3 – stars: individual: SDSS J150551.58+065948.7 – novae, cataclysmic variables – white dwarfs.

1 INTRODUCTION

The AM Canum Venaticorum (AM CVn) binaries are hydrogen-deficient, ultracompact, mass-transferring white dwarf binaries. This rare class of objects is characterized by their short orbital periods, which fall in the range of 5–65 min, and their helium-rich spectra. The white dwarf primary accretes from a degenerate or semidegenerate companion, allowing their periods to fall significantly below the expected period minimum of normal hydrogen-rich cataclysmic variables (~ 80 min; Rappaport, Joss & Webbink 1982; Gänsicke et al. 2009). See Solheim (2010) for a recent review of the AM CVn binaries.

The AM CVn class is of particular interest due to their potential as progenitors of Type Ia supernovae (e.g. Shen & Bildsten 2009, 2014), and sub-luminous SN Ia-like explosions ('SN.Ia'; Bildsten et al. 2007; Brown et al. 2011). They are also extremely important due to their expected gravitational wave emission; AM CVn binaries are predicted to be some of the strongest known sources of low-frequency gravitational waves that would be detected by future space-borne gravitational wave detectors (Roelofs et al.

2006b; Stroeer & Vecchio 2006; Nelemans 2009; Nissanke et al. 2012).

The gravitational wave emission thought to drive the evolution of the AM CVn binaries leads to a strong dependence of the mass accretion rate, and hence their observed properties, on the orbital period. The observational characteristics of an AM CVn binary are commonly separated into four distinct categories, based on a combination of empirical evidence and theoretical models. Direct impact accretion is expected for orbital periods below ~ 10 min (e.g. HM Cnc, Roelofs et al. 2010; V407 Vul, Marsh & Steeghs 2002); in these systems no accretion disc forms. Analogous to cataclysmic variables, where a white dwarf accretes from an H-rich disc, the He-rich discs found in AM CVn stars are subject to a thermal instability (Meyer & Meyer-Hofmeister 1981; Tsugawa & Osaki 1997; Kotko et al. 2012; Ramsay et al. 2012). At short orbital periods (~ 10 to ~ 20 min), the mass transfer rate is sufficiently high to keep the disc in a stable hot, bright state (e.g. HP Lib, O'Donoghue et al. 1994; SDSS J1908+3940, Fontaine et al. 2011). At intermediate orbital periods, the discs undergo quasi-periodic outbursts, cycling between a quiescent faint state with a cool disc, observationally characterized by strong emission lines, and a hot bright state, characterized by absorption lines from the optically thick disc (e.g. CR Boo, Wood et al. 1987; SDSS J0129+3842,

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Shears et al. 2012; PTF1 J0943+1029, Levitan et al. 2013). At the longest orbital periods ($\gtrsim 45$ min), corresponding to the lowest mass transfer rates, the disc is thought to be in a stable faint state, and the spectra of these systems are hence dominated by strong emission lines (e.g. GP Com, Nather, Robinson & Stover 1981; SDSS J1552+3201, Roelofs et al. 2007b).

The first AM CVn binaries were discovered serendipitously in a variety of different ways (e.g. Burbidge & Strittmatter 1971; Israel et al. 1999), producing a small and heterogeneous sample. A total of six new AM CVn binaries were discovered in the Sloan Digital Sky Survey (SDSS; York et al. 2000) I and SDSS-II spectroscopic data, via their helium emission dominated spectra (Anderson et al. 2005, 2008; Roelofs et al. 2005). These provided the first well understood, homogeneous sample, that allowed Roelofs et al. (2007a) to estimate the local space density by calibrating the theoretical population models. Roelofs et al. (2007a) obtained a value of $1\text{--}3 \times 10^{-6} \text{ pc}^{-3}$. This was an order of magnitude lower than the expected space density at the time, derived from population synthesis ($2 \times 10^{-5} \text{ pc}^{-3}$, based on Nelemans et al. 2001).

Since the known AM CVn binaries have been found to occupy a relatively sparsely populated region of colour space, which has a low spectroscopic completeness in the SDSS data base, we have conducted a dedicated spectroscopic survey designed to uncover the ‘hidden’ population of AM CVn binaries in the SDSS photometry. Details of this programme, including the sample selection criteria, and the seven AM CVns discovered, were presented by Roelofs et al. (2009), Rau et al. (2010) and Carter et al. (2013).

We recently presented the latest results from this survey; where we discussed increasing our AM CVn detection efficiency using new colour–colour cuts based on photometry from *GALEX*, and gave our revised estimate of the AM CVn space density, $(5 \pm 3) \times 10^{-7} \text{ pc}^{-3}$ (Carter et al. 2013).

More than a third of the total known population of AM CVn binaries have been discovered via the SDSS, though recently they

have also been found increasingly via synoptic surveys, with the Catalina Real Time Transient Survey (CRTS; Drake et al. 2009), and the Palomar Transient Factory (PTF; Law et al. 2009) significantly increasing the population (Levitan et al. 2011, 2013; Woudt, Warner & Motsoaledi 2013). Here, we present two new systems discovered amongst the SDSS-III spectroscopic data. Motivated by their discovery, we have applied our proposed colour–cuts based on *GALEX*, whilst extending the original colour–selection in the SDSS bands, to search for any further AM CVns in the most recent SDSS spectroscopy.

2 A SEARCH OF THE SDSS SPECTROSCOPIC DATA BASE

The SDSS-III comprises four spectroscopic surveys, largely targeting quasars and galaxies (Eisenstein et al. 2011). Recent data releases have significantly increased the number of spectra available. We discovered the two new systems discussed in this article whilst examining spectra of objects targeted as white dwarfs by the SDSS-III. This motivated us to conduct a fuller search of the SDSS spectroscopic data base, examining objects observed as part of the SDSS-III with colours similar to the known AM CVns (the spectroscopic observations from the SDSS and SDSS-II have been well explored by previous studies, Anderson et al. 2005, 2008; Roelofs et al. 2005).

We have previously exploited the similar colours of the known AM CVns to conduct a dedicated survey of objects with only photometry in the SDSS data base, to search for the ‘hidden’ population (Carter et al. 2013). The two new AM CVns both have $u - g$ colours slightly outside the range occupied by the previously identified SDSS AM CVns, and so we have expanded Roelofs et al. (2009)’s original colour selection for our new search of the spectroscopic data base, as shown in Fig. 1 and Table 1. We also apply our colour–cuts based on *GALEX* near-ultraviolet (NUV) photometry,

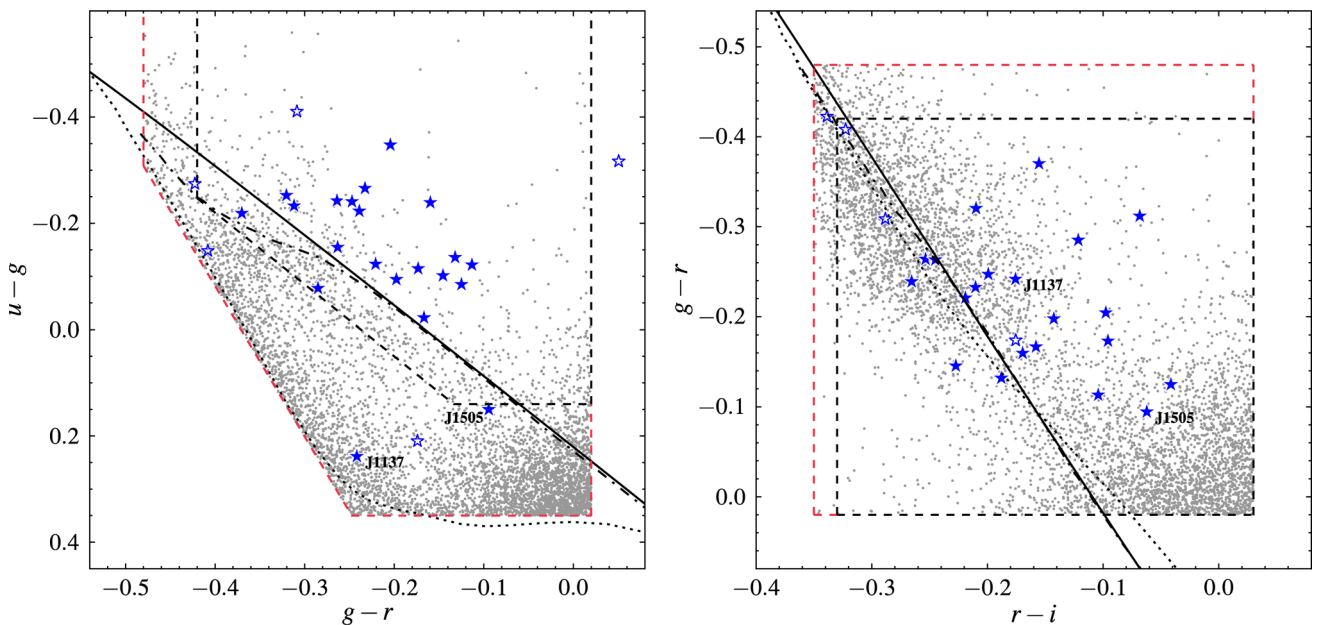


Figure 1. Dereddened colours of the known AM CVn binaries with *ugri* photometry (blue stars). Those systems that have short periods, or photometry that may not correspond to their quiescent state are marked with open stars. The two new AM CVns are labelled. Colours of the faint PTF-discovered systems are taken from Levitan et al. (2013). The black dashed lines show the Roelofs et al. (2009) colour–cuts, the red dashed lines represent the extended cuts we use here. The objects selected are plotted as grey dots. The two AM CVns with $u - g$ outside the original cuts are the new systems discussed in this article. The solid line shows the blackbody cooling track, the dotted and dot–dashed lines represent the DA and DB white dwarf cooling tracks ($\log g = 8.0$).

Table 1. Colour selection used to search for AM CVns in the SDSS spectroscopic data base. We select only objects classified as a point source, with spectra that were made available in SDSS Data Releases 8, 9 or 10.

Colour	Constraint
$u - g$	< 0.35
$u - g$	$< 2.83 (g - r) + 1.05$
$g - r$	< 0.02
$g - r$	> -0.48
$r - i$	< 0.03
$r - i$	> -0.35
$\text{NUV} - u$	$> 4.34 (g - r) + 0.5$ OR < -1
$\text{NUV} - u$	$< 6.76 (r - i) + 1.85$ OR > 1.5

to increase the efficiency of our search, as these remove many of the sub-dwarfs and quasars from the sample (Carter et al. 2013). As described in Carter et al. (2013), we retain objects that have extreme $\text{NUV} - u$ colours (as they may be variable), and those that do not have a match in the *GALEX* data base. Our constraints are summarized in Table 1. We correct colours for Galactic extinction as described by Roelofs et al. (2009) and Carter et al. (2013).

Applying these constraints to SDSS Data Release 10 (DR10), cross-matched with *GALEX* Release 7, resulted in the selection of 5728 objects, for which the spectra were then visually inspected. The main contaminants in this colour-selection are hydrogen atmosphere (DA) white dwarfs, and quasars. We recovered five AM CVns with spectra taken as part of the SDSS-III surveys,¹ including the two new systems, but found no additional new AM CVns.

3 THE NEW AM CVN BINARIES

3.1 Average spectra

We show the SDSS spectra of the two new AM CVn systems, SDSS J113732.32+405458.3 (hereafter SDSS J1137) and SDSS J150551.58+065948.7 (hereafter SDSS J1505) in Fig. 2. These were identified via the strong helium emission lines they display. Their spectra are both remarkably similar to the spectrum of SDSS J1208 from Kupfer et al. (2013), which is reproduced in Fig. 2 for reference. Both SDSS J1137 and SDSS J1505 show triple-peaked emission lines, combining the standard double-peak associated with the accretion disc (Horne & Marsh 1986), and a ‘central spike’. This feature has been seen in several AM CVn systems, and is thought to originate close to the surface of the accreting white dwarf (Marsh 1999; Morales-Rueda et al. 2003). There are signs of underlying absorption around the 5875 Å emission line in both spectra. Similar features have been seen in several AM CVns (e.g. SDSS J1240, V406 Hya Roelofs et al. 2006a), where this is identified as being from the accretor, but it is usually clearest in the bluest lines. Both systems also show broad nitrogen emission lines in the red parts of their spectra (see Fig. 2).

Table 2 gives the SDSS and *GALEX* photometric magnitudes for the two systems. We fitted a blackbody to both the spectrum (masking the emission lines) and the photometric fluxes for each object in order to estimate the continuum temperature. The data have been corrected for extinction using the full Galactic reddening according

to Schlegel, Finkbeiner & Davis (1998), $E(B - V) = 0.018$ and 0.032 for SDSS J1137 and SDSS J1505, respectively. The fits and temperatures are shown in Fig. 3. We give the formal uncertainties from the fits. Note that the contribution of the disc to the continuum is unknown, and is expected to vary significantly with orbital period (see e.g. Nelemans, Yungelson & Portegies Zwart 2004; Bildsten et al. 2006).

3.2 Radial velocities

The SDSS spectra (Fig. 2) are the average of at least three exposures, known as sub-spectra, with typical exposure times of 15 min. There are six sub-spectra for SDSS J1137, and four for SDSS J1505. We searched for radial velocity variations between the SDSS sub-spectra in order to search for the orbital periods of these systems.

We measured the radial velocities of the nine strongest He I emission lines² using MOLLY.³ Each line was fitted by a single Gaussian, with the initial values of the fit parameters determined from a fit to the average spectrum. The full width at half-maximum for each line was fixed to this value, whilst the velocity offset common to all lines, and the height of each line were allowed to vary. This gives a radial velocity for each sub-spectrum that is much more precise than achievable using any single line.

The measured radial velocities, given in Tables 3 and 4, were then used to construct power spectra for each object, to search for periodic signals. We use both the Lomb–Scargle (Lomb 1976; Scargle 1982) and orthogonal polynomial (ORT; Schwarzenberg-Czerny 1996) methods to calculate power spectra. The power spectrum for SDSS J1137 (shown in Fig. 4) is dominated by two strong peaks, corresponding to periods of 22.56 ± 0.39 and 59.63 ± 2.74 min. The phase folded radial velocity curve for the longer period is shown in Fig. 5.

The power spectra for SDSS J1505 produce a similar result, with the stronger peak corresponding to a period of 50.6 min. However, with only four data points, the low radial velocity amplitude and the large uncertainties on the measurements, we do not consider this to be a reliable measurement of the orbital period.

4 DISCUSSION

The spectra of the two new AM CVn binaries are very similar to that of the long-period AM CVn SDSS J1208 ($P_{\text{orb}} = 53$ min; Anderson et al. 2008; Kupfer et al. 2013) showing broad double-peaked helium emission with strong central spikes (Fig. 2). Due to the mass transfer rate being a steep function of the orbital period, the spectra of AM CVn binaries vary considerably with period. That these new systems have spectra that appear similar to SDSS J1208 suggests that they may also be long-period AM CVn binaries ($\gtrsim 50$ min).

The two possible periods determined from radial velocities of the sub-spectra for SDSS J1137 have almost equal power in the power spectra. At an orbital period of 22.5 min, we would expect the system to spend much of its time in a high state, or to undergo frequent outbursts (similarly to KL Dra; Ramsay et al. 2012). On the other hand, at a period of 59.6 min we would not expect to see any outbursts, with the disc being in a stable quiescent state. As there is no evidence of outbursts (or other significant variability) in

¹ The previously known AM CVns with new spectra in the SDSS-III are SDSS J0129+3842, SDSS J0804+1616 and SDSS J1721+2733.

² The following He I emission lines were used to measure the radial velocities: 3888, 4026, 4471, 4921, 5015, 5875, 6678, 7065 and 7281 Å.

³ MOLLY was written by T. R. Marsh and is available at <http://www.warwick.ac.uk/go/trmarsh/software>

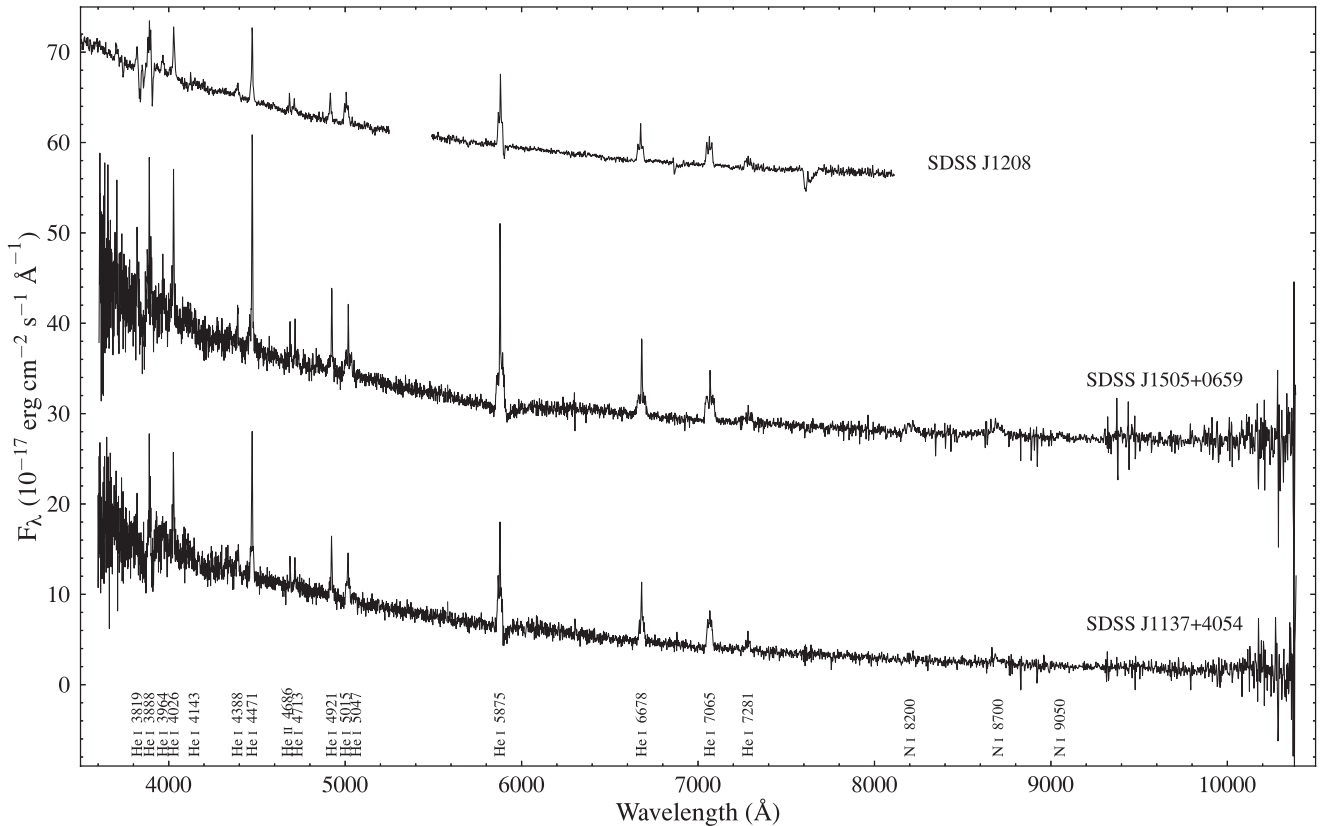


Figure 2. SDSS spectra of the two new AM CVn binaries and SDSS J1208 (Kupfer et al. 2013). The prominent emission lines have been labelled. The spectra of SDSS J1505 and SDSS J1208 have been offset by 25×10^{-17} and $54 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$, respectively.

Table 2. Spectral energy distribution and equivalent width (EW) of the He I 5875 Å emission line for the two new AM CVn binaries. Numbers in parentheses indicate uncertainties in the corresponding number of last digits.

Object	FUV	NUV	<i>u</i>	<i>g</i>	<i>r</i>	<i>i</i>	<i>z</i>	<i>A(g)</i>	EW He I 5875 (Å)
SDSS J113732.32+405458.3	–	19.87(9)	19.26(3)	19.00(1)	19.23(1)	19.39(2)	19.45(6)	0.07	–30(3)
SDSS J150551.58+065948.7	22.69(23)	20.05(17)	19.30(3)	19.11(1)	19.17(1)	19.21(2)	19.35(5)	0.12	–50(3)

the 9 yr coverage of the CRTS (Drake et al. 2009) light curve, and the similarity of SDSS J1137’s spectrum to that of the long-period system SDSS J1208, gives support to the longer of the two possible periods.

The CRTS light curve for SDSS J1505 also shows no sign of any outbursts (though infrequent outbursts could have been missed), and the spectrum is also very similar to that of SDSS J1208 (Fig. 2), again suggesting a long period for this system. We do not consider the periodic signal measured for SDSS J1505 to be a reliable measure of the orbital period due to the paucity of data, but it might lend further support to the suggestion that it is another long-period system.

The chemical abundances of material in the accretion discs of AM CVns can, in principle, be used to infer the formation channel of these systems (Nelemans et al. 2010; defined by the evolutionary state of the donor at the onset of Roche lobe overflow, see e.g. Solheim 2010). The detection of nitrogen emission in the spectra of AM CVn binaries has been used to suggest that they are more likely to have white dwarf donors than helium star donors (e.g. Levitan et al. 2013; Carter et al. 2014). We cannot constrain the N/C ratio as there are no strong carbon lines in the optical, but the detection

of N I lines likely rules out significantly evolved He star donors (Nelemans et al. 2010).

Both spectra show signs of absorption wings around the He I 5875 emission line (especially SDSS J1505), that could be associated with the accreting white dwarf. However, this would require a white dwarf temperature of $\sim 15\,000$ K or higher, which does not seem to be compatible with the NUV flux detected for either system. It is also worth noting that at a period longer than 50 min, such a temperature would be unexpectedly high, as the white dwarf should cool as the orbital period increases (Bildsten et al. 2006). We also note that where DB absorption wings have been observed in other AM CVn binaries, it has been strongest around bluer lines, particularly He I 4471, and has not been noticeable around the 5875 Å line (e.g. Roelofs et al. 2006a). This feature may be due to interstellar Na absorption, SDSS J1137 shows only a red wing, and the red wing appears stronger in SDSS J1505.

The continuum temperatures suggest cool accretors for both systems, this would be expected for long-period systems, and helps to explain the redder than average *u* – *g* colours that push these objects outside of our original colour box. Even considering the low temperature of the accretor, SDSS J1137 has an extremely red

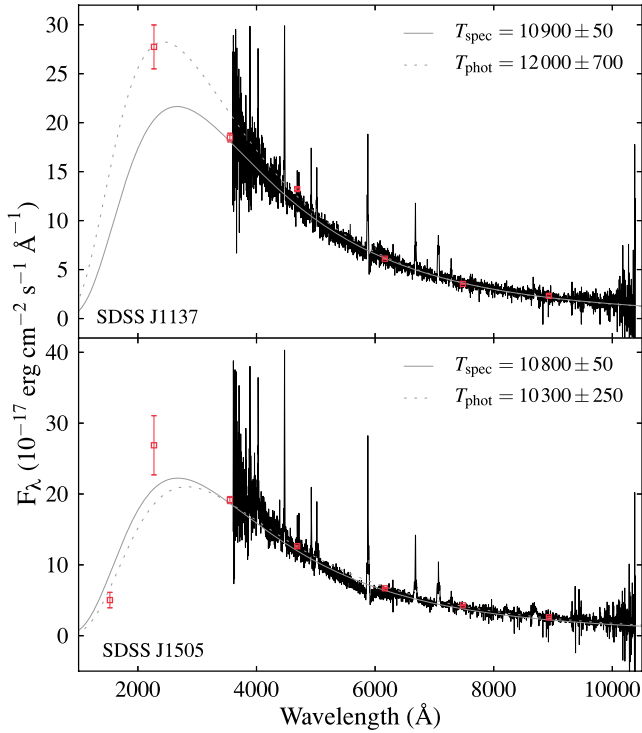


Figure 3. Spectra of the two new AM CVn binaries with photometric data from SDSS and *GALEX* overplotted (red squares). The solid and dashed lines are blackbody fits to the spectra and photometry, respectively. Temperatures of these fits are given in Kelvin. Data have been corrected for Galactic extinction.

Table 3. Radial velocities measured from the SDSS J1137 sub-spectra.

HJD	Radial velocity (km s ⁻¹)
2455620.8272816	38.20 ± 16.85
2455620.8386465	102.47 ± 19.84
2455620.8500112	-24.08 ± 18.58
2455620.8613760	-13.26 ± 19.39
2455620.8727523	95.37 ± 14.75
2455620.8841171	89.73 ± 14.71

Table 4. Radial velocities measured from the SDSS J1505 sub-spectra.

HJD	Radial velocity (km s ⁻¹)
2455712.6830284	76.53 ± 27.44
2455712.6944161	54.92 ± 28.41
2455712.7057808	87.89 ± 26.39
2455712.7171455	94.27 ± 24.99

$u - g$ colour that puts it surprisingly close to the DA white dwarf track in $u - g$, $g - r$ colour space (see Fig. 1).

That we found no further new systems in our search of the SDSS spectroscopic data base leads us to suspect that these two systems are outliers from the main colour distribution of AM CVn binaries. If they represent an additional population that is missed in our earlier systematic search (Carter et al. 2013), then this population is likely small, since there are only two such systems in the SDSS spectroscopic data base (compared to the nine systems with SDSS spectra in Roelofs et al. 2009's original colour box). The discovery

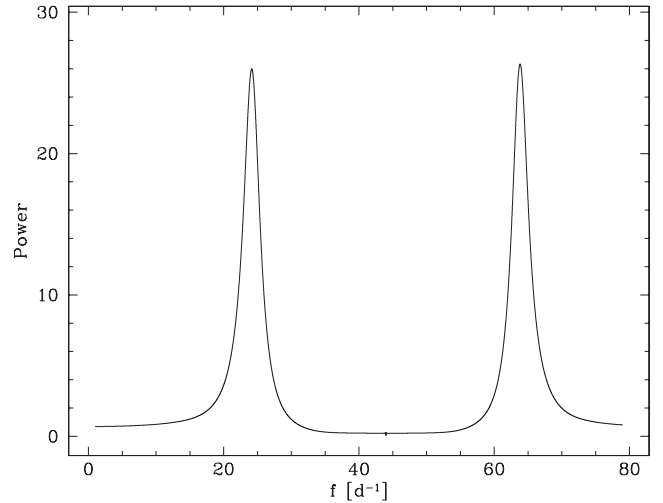


Figure 4. ORT power spectrum calculated from the He I radial velocities of SDSS J1137. Two strong peaks of almost equal power are seen at 24.1 and 63.8 cycles d⁻¹.

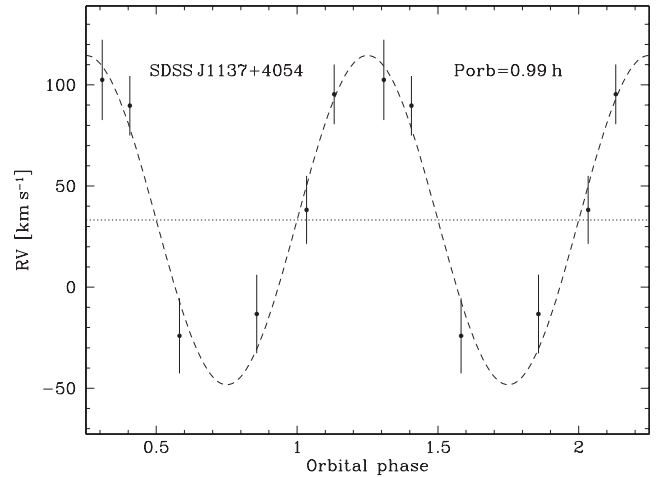


Figure 5. Measured He I radial velocities for SDSS J1137 folded on a period of 59.6 min. The dashed and dotted lines are the best fitting radial velocity curve and systemic velocity.

of these two new AM CVns should have very little effect upon previous estimates of the AM CVn space density.

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<http://www.sdss3.org/>. This research has made use of NASA's Astrophysics Data System. Fig. 1 makes use of P. Bergeron's synthetic white dwarf colours (Holberg & Bergeron 2006; Kowalski & Saumon 2006; Bergeron et al. 2011; Tremblay, Bergeron & Gianninas 2011), kindly made available by the authors at <http://www.astro.umontreal.ca/~bergeron/CoolingModels>.

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